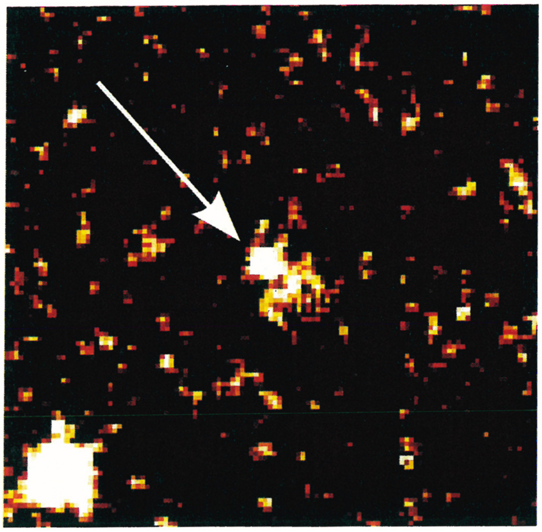

HUBBLE SPACE TELESCOPE image of the optical afterglow of the 28 February gamma ray burster combines the observations of 26 March and 7 April. The arrow indicates the pointlike optical transient, which faded from magnitude 21.3 one day after the burst to magnitude 26.4 on 7 April. To the transient's immediate lower right is a persistent faint extended object that may be its parent galaxy. The bright foreground star in the lower left corner is 3 arcseconds away. (Image courtesy of K. Saha, Space Telescope Science Institute.)

William Herschel Telescope in the Canary Islands that very night, for a completely unrelated purpose. Sure enough, 21 hours after the first BeppoSAX observation, van Paradijs's group had an optical image of a faint point object, within the wide-field camera's error box, that was no longer visible when the Herschel telescope looked again on 8 March. Subsequent analysis confirmed that the image of the optical transient had been within the tight positional contraints imposed by the narrow-field x-ray image and long-baseline timing data from two other satellites. (See the figure on page 17.)

Now it was time to enlist more powerful eyes. A week after it had faded from view at the Herschel, the optical transient could no longer be seen as a point source by the New Technology Telescope in the Chilean Andes or the 10-meter Keck telescope in Hawaii. But those powerful telescopes did detect a faint extended object, perhaps a galaxy, just where the transient had been.

On 26 March the Hubble Space Telescope (HST) got into the act. Unencumbered by atmospheric blurring, it could still see the transient, now almost 100 times fainter than when the Herschel telescope had seen it. The HST image (see above) also made it clear that the pointlike transient was near the edge of the extended object and certainly not at its center. When the HST looked again on 7 April, the transient was still visible, but it had faded by another 30%. The extended object, by contrast, has not shown any obvious fading.[2] The Hubble telescope will now have to wait until August for the Sun to get out of the way, before it can look again.

If the fuzzy object turns out to be a faint galaxy, that will lend strong support to the majority opinion that GRBs are indeed at cosmological distances and are therefore the brightest phenomena in the universe. An independent analysis of the HST images by Patricia Caraveo and colleagues at the University of Milan concludes that the optical transient moved perceptibly from the one Hubble sighting to the next. That would, of course, mean that the object is well inside our own Galaxy. If that's true, it would be difficult to explain why the distribution of GRBs on the sky is so very isotropic. But the HST team strongly asserts that there is no evidence of such "proper motion." In any case, one cannot yet exclude the possibility that the fuzzball belongs to a class of previously unrecognized objects in the outskirts of our Galaxy.

Nowadays, BATSE leader Gerald Fishman and his colleagues eat and sleep with special beepers always at their sides. The purpose is to alert them as soon as the next bright GRB is sighted so that, with the help of the recently launched Rossi X-Ray Timing Explorer, they can provide a prompt and precise fix on its celestial coordinates to a long list of waiting optical, x-ray and radiotelescopes.

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Can Phonons Squeeze their Way Into the Company of Photons?

Twelve years ago, Richart Slusher and his colleagues at AT&T Bell Labs produced light whose noise was below the vacuum quantum fluctuations, at least in part of the signal.[1] Since then, researchers have been trying to squeeze the uncertainties out of other systems as well. So far they have succeeded in quieting a classical mechanical oscillator[2] and both classical[3] and nonclassical[4] states of a vibrating, trapped ion. Now comes a report of squeezed phonons: By striking a crystal with a femtosecond laser pulse, a group at the University of Michigan believes it has excited an acoustic mode whose variance falls below the standard quantum limit.[5] So far, the noise has been reduced by only 0.01% (the earliest experiments on optical squeezing yielded 20%), but just the concept of squeezed phonons has intrigued many observers.

> The noise can be squeezed out of a light signal until it falls considerably below the quantum, or shot, limit. Now researchers are trying to use a similar trick to reduce the noise associated with phonons.

Squeezing is a trade-off

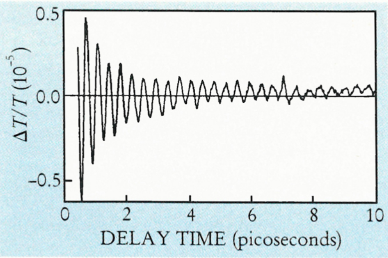
If you squeeze a wad of putty in your hand, some of it will ooze out between your fingers. In the same way, reducing the noise in one variable of a quantum system makes the noise grow in the complementary variable. The two so-called quadrature variables are linked by the Heisenberg uncertainty principle, which places a lower limit on the product of uncertainties in them. For a mechanical system, the complementary variables may be position and momentum; for a light wave, they mey be the electric and magnetic field vectors.

The vibrating atoms in a solid follow the same rules: Even at absolute zero, the atoms undergo quantum oscillations about their equilibrium positions, with the motions obeying $\Delta x \, \Delta p \geq \hbar$. These oscillations are equivalent to the vacuum fluctuations of an electromagnetic field and constitute the fundamental limit to any measurement.

At the University of Michigan, Gregory Garrett, Alberto Rojo, John Whitaker and Roberto Merlin, together with Ajay Sood from the Indian Institute of Science in Bangalore, set out to generate a squeezed phonon state in a crystal of potassium tantalate ($KTaO_3$) by striking the crystal with a 70-femtosecond laser pulse whose wavelength is 810 nm. The pulse interacts with the crystal by second-order impulse stimulated Raman scattering in which the photon is scattered inelastically, creating two phonons in the process. Before the pump pulse strikes, the atoms of the crystal are oscillating with random phases relative to one another. According to Merlin, the pulse then delivers an impulsive force whose magnitude is proportional to the displacement of a given atom from equilibrium: Atoms with a larger displacement receive a larger kick. The net result is to bring the fluctuations more in step with one another. Right after the pulse hits, the amplitudes of all fluctuations are reduced. As time goes on, the size of the fluctuations grows and then shrinks again, in a periodic fashion.

Of course, one can't tell if a squeezed state has been generated until it is measured. In optics, squeezed light is detected by a phase-sensitive method because the degree of squeezing varies with the phase of the electric field. There is no comparable technique available in the phonon case. The Michigan group was able to use pulses as short as a few tens of femtoseconds to trace the evolution of a squeezed state with very fine time resolution. Each pump pulse is followed, after a variable time delay, by a probe pulse, whose transmission depends on the refractive index of the crystal, which in turn is sensitive to the mean square displacement of the atomic positions. Any modulations in the mean square displacement should show up as a change in transmission. Thus, Merlin and his group measured the fractional change in transmission of the probe pulse. That gave them the variance at one particular phase and in one quadrature of the excited phonon. To sample the crystal at another phase, the group changed the time delay of the probe pulse. In this way, they recorded a sinusoidal oscillation of the variance. See the figure above. The figure traces the evolution as a function of phase, provided one assumes that each pump pulse sets the crystal off in the same phase.

Couldn't a sinusoidal signal like the differential transmission simply reflect the stimulation of some kind of oscillation in the crystal? No, according to the Michigan researchers. They expect the net displacement of any oscillation to be zero because the coupling of the light to the crystal is only second order. Thus the variance—that is, the



THE CHANGE IN TRANSMISSION of a probe pulse through a crystal of potassium tantalate, as a fraction of the transmission. The change is plotted against the delay time since the passage of a pump pulse. The signal, which is sensitive to the variance, oscillates periodically with the delay time. From these data, University of Michigan researchers inferred a measure of phonon squeezing. The signal eventually damps out. Adapted from ref. 5.

expectation value of the square of the displacement minus the square of the expectation value of the displacement—is just the mean square displacement. If the phonon were not squeezed, they would expect this term to be constant.

From their measurements, the researchers deduced the relative variance—that is, the difference between the observed variance and the variance at absolute zero (the zero-point motion), normalized by the zero-point motion. The squeezing factor, the amount by which the relative variance fell below zero, was on the order of 10^{-4} in their most recent experiments, Merlin told us. He hopes that his team can reduce the noise even more by working with a laser that is closer to a resonance, where the nonlinear effects are greater.

This phonon experiment is complicated by the presence of a continuum of phonon modes. Discussions of squeezing usually focus on a single phonon mode, but in reality there are many modes. Merlin and his colleagues feel that their method of generating a squeezed state selects a subset of modes with similar frequencies. The $KTaO_3$ crystal is known to have a large peak in the phonon density of states at around 1.4 THz, associated with a van Hove singularity. (A van Hove singularity is a cusp or dip in the plot of frequency versus wavenumber at which a large number of states are clustered in a narrow range of frequencies.) As evidence that they are exciting this band of states, the researchers point out that the Fourier transform of the measured variance peaks at twice the frequency associated with the van Hove singularity. The interference among the modes at slightly different wavevectors damps out the variance seen in the figure.

Applications

The first reports of squeezed light were accompanied by high hopes for better measurements, especially for gravity-wave detectors, and for more noise-free communications. These applications have not yet been realized but they remain very real possibilities. The practical applications of squeezed phonons are not as obvious, especially if one can achieve only small amounts of squeezing. Nevertheless, the possibility of squeezing is quite intriguing for fundamental explorations. It would be interesting, mused Slusher, to see what squeezed phonons might do as they interact with other excitations in solids. For example, how might the interaction affect the coupling between carriers in a superconductor or the scattering of carriers in a regular conductor?

A few theorists have studied the possibilities of squeezed phonons. At the City College of the City University of New York, Maurizio Artoni and Joseph Birman proposed squeezing polaritons, mixed polarization modes in crystals.[6] Loosely speaking, polaritons represent a coupling of photons and phonons or, at higher energies, of photons and excitons. With these hybrid objects, Birman feels, one could tune the degree of squeezing and get greater amounts of squeezing.

At the University of Michigan, Franco Nori and Xuedong Hu (who is now at the University of Illinois at Chicago) have investigated squeezed and quantum coherent phonon states, as well as polaritons.[7] They have discussed various schemes for the generation of squeezed phonons, including stimulated Raman scattering, and for their detection, including the reflectivity of a probe beam.

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